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## Numerical Simulation of Coughed Droplets in the Air-Conditioning Room

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### Abstract

The public pay close attention to infectious disease transmission in the indoor environments since the outbreak of severe acute respiratory infectious diseases. This paper studies the spatial distribution and temporal evolution of coughed droplets with the size of 10 $\mu$ m in the air-conditioning room of two ventilation patterns, specifically mixing ventilation (MV) and displacement ventilation (DV). There are two people standing face to face with a distance of 0.5m, 0.75m and 1m. RNG  $k$ - $\epsilon$  turbulent model is used to simulate indoor airflow. The diffusion, gravitational settling and deposition mechanism of coughed droplets matter are simulated by using Lagrangian method. The simulation results indicate that the temperature is uniform in MV, while it is not in DV. DV is easier to discharge the coughed droplets and reduce infection rates. The closer distance between human bodies can increase infection rates.

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**Keywords:** Coughed droplets; Ventilation; Airflow; Numerical simulation; Air-conditioning room

### 1. Introduction

In modern society, people spent much more time in the closed air-conditioning room, which could mean they are more susceptible to respiratory infectious diseases. The common respiratory infectious diseases are influenza, mumps, measles, rubella and varicella. The new respiratory infectious diseases are SARS, H5N1 avian influenza virus, H7N9 avian influenza virus and H1N1 virus. The diseases cause great economic losses to the state and threaten human health.

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When people speak, breath, cough or sneeze, droplets carrying viruses can be released from nose and mouth. The reasonable ventilation patterns can discharge droplets as soon as possible and reduce infection rates.

In recent years, with the outbreak of severe acute respiratory infectious diseases, a lot of studies have been done for droplets. The main research methods include experiment and CFD numerical simulation. Shi et al. [1] use experiment to study the attenuation law of concentration of different size droplets in different room air changes. Gao et al. [2] use high-precision aerosol spectrometer to measure indoor droplets concentration. Comparing with experiment, CFD numerical simulation has the advantages of simple operation and low cost, which is widely applied to studying the indoor droplets distribution by a large number of scholars. With an airborne infection isolation room as study place, Jennifer [3] uses CFD numerical simulation to study velocity and concentration of droplets released by patient. With a bus as study place, Zhu et al. [4] use CFD numerical simulation to compare the influence caused by three kinds of MV and DV on droplets motion. This paper analyzes coughed droplets distribution in MV and DV in the air-conditioning room by CFD numerical simulation.

### Nomenclature

$\rho$	air density
$V$	velocity vector
$\phi$	each of the three velocity components ( $u, v, w$ )
$\Gamma_\phi$	effective diffusion coefficient for each dependent variable
$S_\phi$	source term
$u_{pi}$	velocity of the particles in the $i$ direction, m/s
$F_i$	all units mass forces are exerted on the particles in the $i$ direction, m/s <sup>2</sup>
$F_d$	drag force, m/s <sup>2</sup>
$G$	gravitation, m/s <sup>2</sup>
$F_{ai}$	additional forces, m/s <sup>2</sup>

## 2. METHODS

### 2.1. Case description

Simplified a complex room into a simple parallelepiped geometry can accelerate the speed of calculation. Muia [5] and He et al. [6] respectively establish simple parallelepiped geometries with sizes:  $X \times Y \times Z = 4.5\text{m} \times 3.5\text{m} \times 2.7\text{m}$  and  $X \times Y \times Z = 4.8\text{m} \times 5.4\text{m} \times 2.6\text{m}$  to study the droplets distribution of in different ventilation patterns. In this paper, the geometry of the air-conditioning room is  $X \times Y \times Z = 4\text{m} \times 5\text{m} \times 3\text{m}$ . Figure 1 illustrates the configuration of the simulated air-conditioning room. There are two people standing face to face with a distance of 0.5m, 0.75m and 1m. The person on the left who releases coughed droplets is assumed as a polluter, and the one on the right is treated as a receptor. This paper generally simplifies the human body model as four parts: head, torso, arms and legs, and Table 1 illustrates detailed sizes. The size of mouth is  $X \times Z = 0.02\text{m} \times 0.01\text{m}$  [6-8].

The temperature of supplied air is maintained at 293K for MV and 295K for DV. The velocity of supplied air is maintained at 2m/s for MV and 0.23m/s for DV. The heat flux released from the human bodies is 40W/m<sup>2</sup>. The temperature is maintained at 304K for the human bodies and 309K for the window. Ceiling, floor and around walls are assumed adiabatic walls. The temperature of expelled air is set to be 308K [6] [9], and the initial velocity is 10m/s [10]. The particle size of coughed droplets is 10 $\mu\text{m}$ , the total flow rate is 2.4e-9kg/s [11], and density is 1000kg/m<sup>3</sup>. The duration of a single cough is assumed to be 1s. The airflow direction of the single cough is 150° to the positive z axis [12].

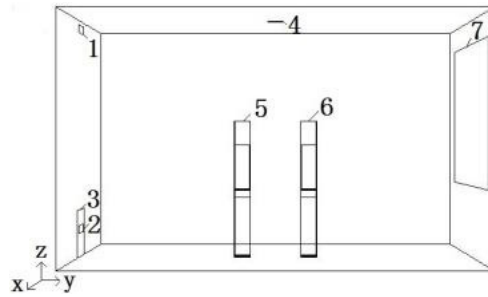


Fig. 1. Configuration of the simulated air-conditioning room

1-MV inlet (0.4m×0.1m); 2-MV outlet (0.4m×0.1m); 3-DV inlet (0.6m×0.6m); 4-DV outlet (0.2m×0.2m);

5-Polluter; 6- Receptor; 7-Window (3m×1.8m)

Table 1. Detailed sizes of the human body model

Parts	Human body model sizes (m)		
	X	Y	Z
Head	0.15	0.2	0.305
Torso	0.3	0.2	0.675
Arms	0.1	0.2	0.575
Legs	0.1	0.2	0.75

## 2.2. Mathematical models

Indoor airflow is generally turbulent. At present, the calculation of turbulent numerical methods can be roughly divided into three: DNS (Direct Numerical Simulation), LES (Large Eddy Simulation) and RANS (Reynolds-Averaged Navier-Stokes). RNG  $k-\varepsilon$  turbulent model based on RANS is more applicable to simulate indoor airflow. Li et.al [13], Zhang and Li [12] use RNG  $k-\varepsilon$  turbulent model to simulate indoor airflow when they study droplets distribution. In this paper, RNG  $k-\varepsilon$  turbulent model is applied. The governing equations, including continuity, momentum, energy, turbulent kinetic energy  $k$  and turbulent dissipation rate  $\varepsilon$ , can be written in the general format as follow [7]. When  $\phi=1$ , the equation becomes the continuity equation.

$$\frac{\partial(\rho\phi)}{\partial t} + \nabla \cdot (\rho\phi V) = \nabla \cdot (\Gamma_\phi \nabla \phi) + S_\phi \quad (1)$$

There are mainly two kinds of methods to simulate the movement of particles: Lagrangian method and Eulerian method. The Lagrangian method is more suitable for the gas-solid two-phase flow whose particle phase is sparse, and it can track particle trajectory. Therefore, Lagrangian method is chosen. The Lagrangian method solves the following equation of motion of single particle or group to obtain velocity and integrate time and then gets trajectory:

$$\frac{du_{pi}}{dt} = F_i \quad (2)$$

$$F_i = F_d + G + F_{ai} [14] \quad (3)$$

$F_{ai}$  is the additional forces (besides drag force and gravity) exerted on unit particle mass, mainly including thermophoretic force, added mass force, basset force, brownian force, saffman force and pressure gradient force. Floating droplets is mainly due to gravity, drag force and Brownian force [15]. In order to simplify calculation,  $F_{ai}$  only includes Brownian force.

### 3. RESULTS

#### 3.1. Temperature field

The temperature fields are shown for MV and DV in Figure 2. The air temperature close to the person is slightly higher because of the heat flux released from the human bodies. In MV, the inlet is close to the ceiling. One side of the jet flow attached ceiling can't roll the surrounding air, so flow velocity is high and pressure is low. The other side of the jet flow isn't limited by the ceiling and can exchange momentum, heat and mass with the surrounding air freely, so flow velocity is small and pressure is high. Hence the difference of upper and lower pressure raises the jet flow, which form wall attached jet. The air flows to the window along the ceiling, which effectively prevents the outdoor heat transferring to the indoor through the window. An eddy is formed at the back part of the head of the receptor, the working area is in the recirculation zone, the indoor temperature is uniform, and the average temperature is 23°C. In DV, the low temperature and low turbulent air flows along the floor and an eddy is formed at the back of the receptor. Because the air temperature is high and the flow velocity is low, which could not effectively prevent the outdoor heat transferring to the indoor through the window. The average temperature near the window is higher than the indoor. The distance between the human bodies has little effect on the air temperature distribution.

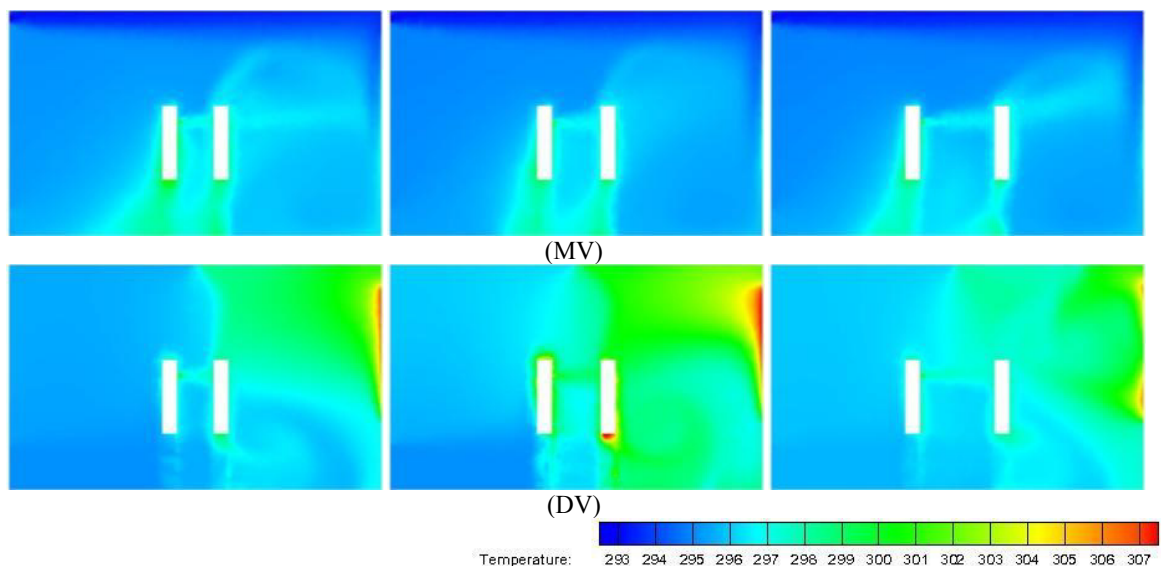


Fig. 2. Temperature contour of plane  $x=0$  in MV and DV, Distance between human bodies = 0.5m, 0.75m and 1m

#### 3.2. Coughed droplets distribution

At 1s, 10s, 50s and 100s, the coughed droplets distribution is shown for MV in Figure 3 and for DV in Figure 4. It can be seen from the figures that coughed droplets of 10 $\mu$ m move for a short distance after releasing from mouth and then begin to spread follow the indoor air. In MV, when the distance is 0.5m, coughed droplets arrive at the receptor at 1s. When the distance is 0.75m, coughed droplets arrive at the receptor at 1~5s. When the distance is 1m, coughed droplets arrive at the receptor at 5s. At 50s, the coughed droplets mainly stay at the eddy which is at the back part of the head of the receptor. The coughed droplets distribution of three cases is similar at 100s, which is at the lower part of the room. In DV, the coughed droplets distribution is similar with MV at 1s and 5s. Because the outlet is at the ceiling, coughed droplets distribution is at the upper part of the room, which is more easily discharged. The distance between human bodies has influence on coughed droplets distribution. Because of shelter from the receptor, the closer

distance can effectively prevent coughed droplets spreading and accelerate the discharge speed. But at the same time the closer distance can increase infection rates of the receptor.

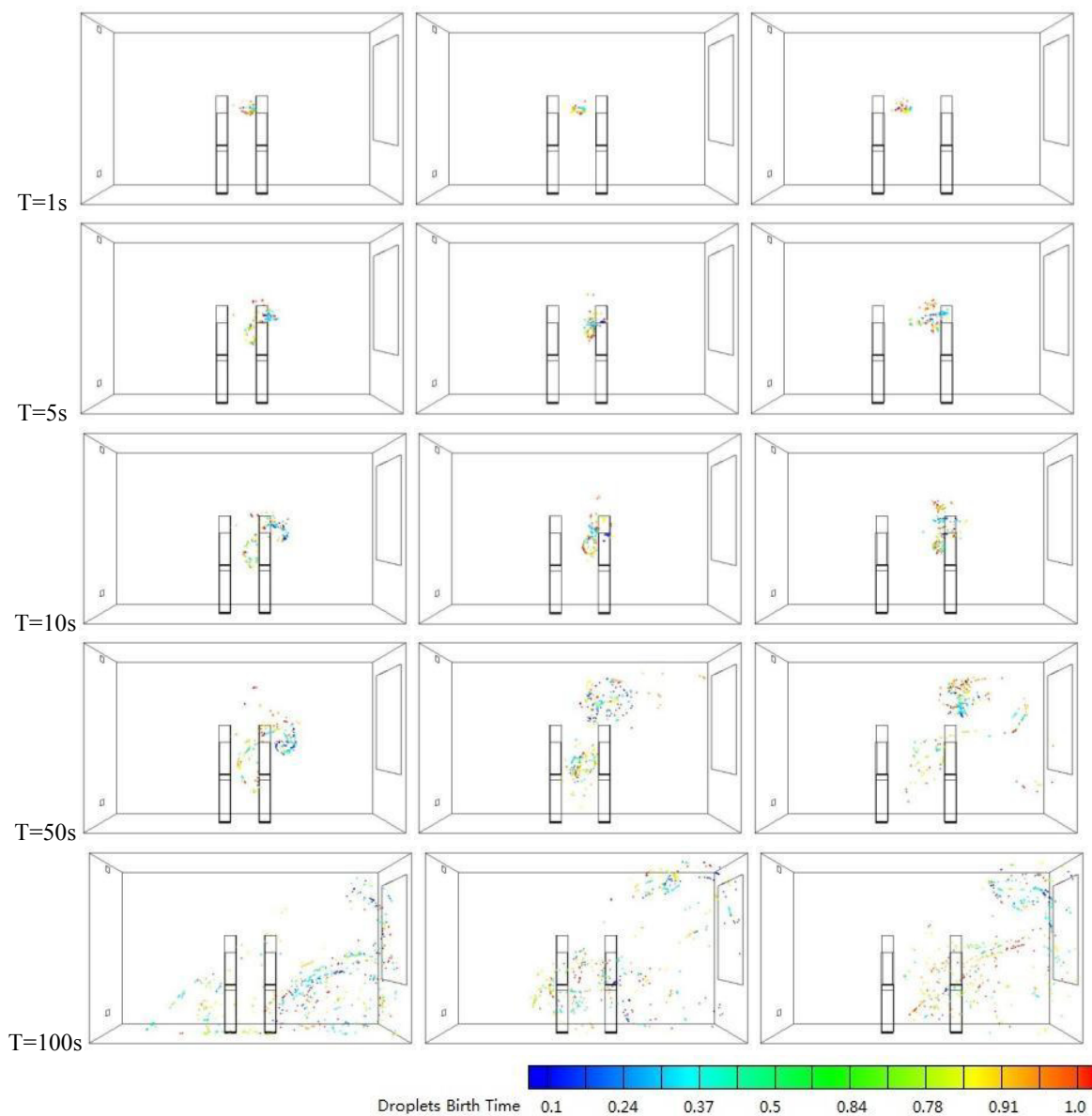


Fig. 3. Coughed droplets distribution in MV, Distance between human bodies=0.5m, 0.75m and 1m, Time=1s, 5s, 10s, 50s, 100s

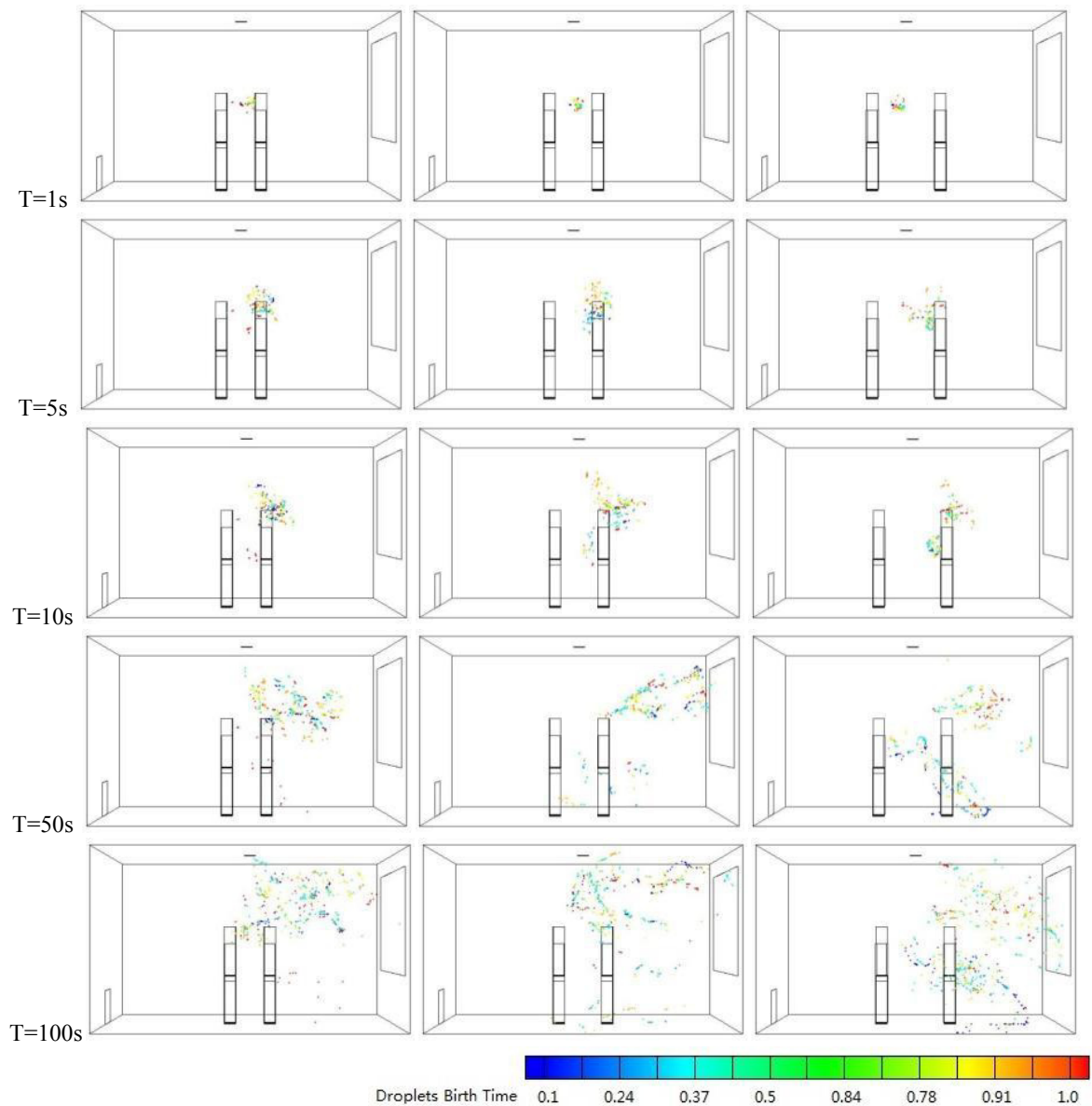


Fig. 4. Coughed droplets distribution in DV, Distance between human bodies=0.5m, 0.75m and 1m, Time=1s, 5s, 10s, 50s, 100s

#### 4. Discussion

In order to simplify the calculation, some assumptions have been made in the simulation process. The assumptions are shown as follows.

- The heat transfer between the coughed droplets and air is neglected, which isn't considering the evaporation of the coughed droplets.
- The collision and cohesion are not occurred between coughed droplets, that the size of coughed droplets isn't change.

- Coughed droplets don't have influence on the indoor airflow. Because the volume fraction of the coughed droplets in the indoor environment is small, the terminal velocity of coughed droplets has little influence on indoor turbulence [16].

The most significant shortcoming of this preliminary study is the lack of the field measurement of the airflow temperature and droplet distribution. Besides, the distance between two human bodies is fixed at 0.5m, 0.75m and 1m, which isn't continuous within the range of 0.5m~1m.

## Conclusions

This paper uses Lagrangian method to study coughed droplets with the size of 10 $\mu$ m in the air-conditioning room. Compare temperature field and coughed droplets distribution in MV and DV. The main conclusions can be drawn as follows.

- The temperature is uniform in MV, while it is not in DV. So people feel comfortable in DV.
- The low speed and low turbulent airflow from the bottom up, such as displacement ventilation, is easier to discharge the coughed droplets and reduce infection rates.
- The initial conditions of expelled air are the main factors which affect coughed droplets distribution preceding 5s. The indoor airflow is the main factor after 5s.
- The closer distance between human bodies can increase infection rates. But, in MV the distance has little influence on coughed droplets distribution, while in DV the closer distance can effectively prevent coughed droplets spreading and accelerate the discharge speed.

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